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# DISCOVERY OF A 69 MILLISECOND X-RAY PULSAR: A COMPACT SOURCE IN THE VICINITY OF THE SUPERNOVA REMNANT RCW 103

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## ABSTRACT

We report a rare discovery of a fast (69 ms) pulsar using X-ray data acquired with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*). The highly significant detection arises from the serendipitous *ASCA* X-ray source AXS J161730−505505, located near the young Galactic supernova remnant (SNR) RCW 103. The epoch-folded light curve displays a single asymmetric pulse profile with a pulse fraction of ∼50%. Spectral fits to the high-energy (i.e., greater than 3.5 keV) source data using a simple absorbed power-law model, assuming the hydrogen column density to the SNR, gives a photon index of $\gamma = 1.6^{+0.2}_{-0.3}$ and an unabsorbed flux of $\sim 6.4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. The extracted source spectrum below 3.5 keV is contaminated by mirror-scattered soft thermal emission from the ∼9′ diameter RCW 103, whose projected center is located just ∼7′ away. If the pulsar is associated with the remnant, the implied neutron star velocity is at the high end of the pulsar velocity distribution for the distance estimates to the remnant but still plausible. We suggest that AXS J161730−505505 is likely a young rotation-powered pulsar with a characteristic spin-down age of ∼8000 yr. The physical association of the pulsar with RCW 103 and its central source, 1E 161348−5055, remains intriguing.

*Subject headings:* pulsars: general — pulsars: individual (AXS J161730−505505) — supernova remnants — X-rays: general

## 1. INTRODUCTION

Rotation-powered plerionic pulsars (Weiler & Panagia 1978) are rare examples of neutron stars associated with young supernova remnants (SNRs). The evolutionary sequence of this class of objects is poorly understood because of the limited number of known objects. There are only three well-established members of this class, whose characteristic age is less than 2000 yr, of which the prototypical Crab pulsar, with a spin period of 33 ms, is the fastest. The other members include the 150 ms pulsar PSR B1509−58 (Seward & Harnden 1982) in the SNR MSH 15−52 (e.g., Tamura et al. 1996; Brazier & Becker 1997) and the 50 ms pulsar PSR B0540−69 (Seward, Harnden, & Helfand 1984) in the Large Magellanic Cloud (LMC). Several candidates for young Crablike pulsars exist, such as 3C 58 (e.g., Helfand, Becker, & White 1995; Torii et al. 1998) and the newly discovered 65 ms pulsar within the SNR G11.2−0.3, a candidate for the historical supernova SN 386 (see Torii et al. 1997 and references therein).

Recently, broadband X-ray observations with *ASCA* (0.5–10 keV) have revealed new properties of composite SNRs by means of spectrally resolving the central compact sources from their surrounding thermal shells (e.g., Vasisht & Gotthelf 1997; Gotthelf & Vasisht 1997). Gotthelf, Petre, & Hwang (1997) have confirmed the existence of an *Einstein* source, 1E 161348−5055 (Tuohy & Garmire 1980), near the center of the Galactic shell-type SNR RCW 103 (G332.4−0.4). Gotthelf et al. (1997) claim that this source is prototypical of a growing class of remnants with central radio-quiet neutron stars, which lack evidence for plerionic emission from a synchrotron nebula, like those of CTB 109, Puppis A, G296.5+10.0, and Kes 73 (Gotthelf et al. 1997 and references therein).

X-ray observations with the *Ginga* observatory of the field containing RCW 103 have revealed 69.319 ms pulsations (Aoki, Dotani, & Mitsuda 1992) in the 1.1 × 2.0 deg$^2$ field of view of *Ginga*'s large area counter. Gotthelf et al. (1997) failed to detect any coherent pulsations from the compact source 1E 161348−5055 with an upper limit of 13% at the 90% confidence level. Gotthelf et al. (1997) serendipitously discovered a hard X-ray source, AXS J161730−505505, located ∼ 7′ due north of the projected center of the SNR shell. Because of the lack of evidence for this object in the (many) archival images of this field, they suggested that the source might be a hard X-ray transient. Stimulated by their work, we reexamined the same *ASCA* data in light of the discovery of two compact sources in the *ASCA* field of view. In this Letter we present the discovery of 69 ms pulsations from one of these compact sources, AXS J161730−505505. In the following discussion, we assume the distance to RCW 103 to be $d_{3.3}$, the source distance in units of 3.3 kpc (Caswell et al. 1975).

## 2. OBSERVATION AND ANALYSIS

The supernova remnant RCW 103 was observed by *ASCA* (Tanaka, Inoue, & Holt 1994) from 1993 August 17 21:33 UT to August 18 15:09 UT during the performance verification (PV) phase of the mission. Details of this observation can be found in Gotthelf et al. (1997). In this Letter we concentrate on data acquired with the two gas-imaging spectrometers (GISs) (Ohashi et al. 1996; Makishima et al. 1996) aboard *ASCA*. These instruments offer the high time resolution necessary for a timing study, with 1/16384 and 1/2048 s time-tagged photons in high and medium bit rate modes, respectively. The standard REV1 data screening procedure was applied to the data (Seufert 1995).

As with the SIS image, the X-ray image of the GIS field of

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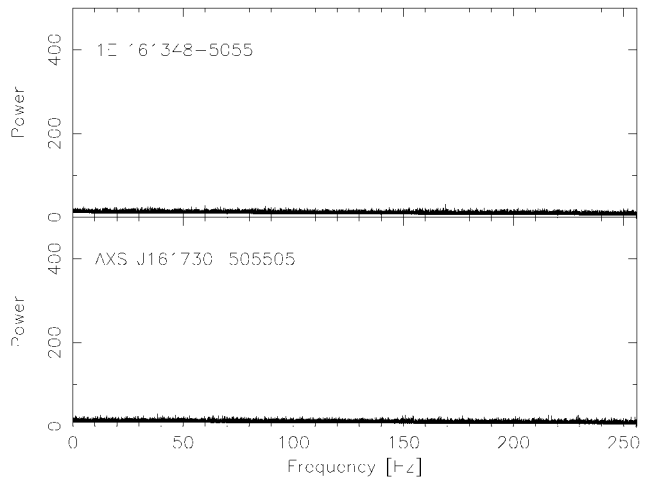


FIG. 1.—Power spectrum of the two hard sources in the GIS field of view: 1E 161348−5055 (*top panel*) and AXS J161730−505505 (*bottom panel*). The energy range is 3–10 keV, and the extraction region is 8′ in diameter. The power is normalized so that the value for random fluctuation is 2 and the data points whose power is 5 times larger than the average power are plotted.

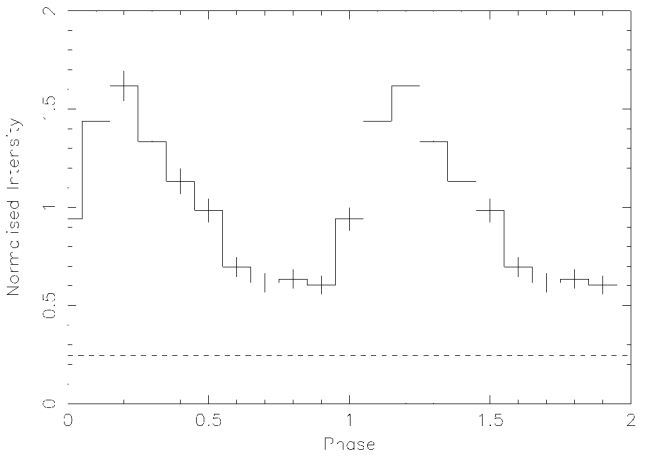


FIG. 2.—Folded light curve of AXS J161730−505505 in the 3–10 keV energy band. Two complete cycles have been plotted. Dashed line shows the estimated background level. The folding epoch is MJD 49216.0.

view above 3 keV reveals two unresolved point sources: 1E 161348−5055, centered on the remnant, and AXS J161730−505505, 7′ due north. Although the remnant is 9′ in diameter, below 3 keV both sources are obscured by soft thermal emission from the SNR shell. This is because of photon scattering by the broad wing of the X-ray telescope point-spread function and the limited spatial resolution of the GIS (∼3′), both of which cause substantial emission interior to the SNR shell and exterior in the region of the serendipitous source. To minimize source contamination from the nebula, we extracted data within a 4′ aperture from each of the two sources, restricted to the 3–10 keV energy band. Event data from GIS2 and GIS3 were co-added, barycentric corrected, binned into $2^{25}$ time steps of 1/512 s resolution, and then Fourier transformed. About 4200 and 2700 events were collected from 1E 161348−5055 and AXS J161730−505505, respectively, of which about 660 events for each source aperture are estimated to be from the background. Figure 1 shows the power spectral densities (PSDs) thus obtained.

As previously reported by Gotthelf et al. (1997), we also do not find any significant pulsation from the source 1E 161348−5055. In Figure 1, we do find a significant signal (∼300, $\chi^2_\nu \sim 150$) in the PSD from AXS J161730−505505 at the search frequency of $f = 14.422104$ Hz. To pin down the period more precisely, we performed an epoch-folding search with 10 phase bins per period and obtained the revised period of $P = 0.06933802 \pm 0.00000003$ s, assuming a zero period derivative.

In order to check that the detected pulsation from the source AXS J161730−505505 was not due to any instrumental artifact, we calculated the PSD for the off-source events and found no significant pulsations. Thus we conclude that we have indeed found a new pulsar associated with the serendipitous X-ray source AXS J161730−505505.

Figure 2 presents a folded light curve, epoch MJD 49216.0, which is constructed using photons in the energy range 3–10 keV. The pulse amplitude is ∼50% of the mean flux, and the pulse shape is singly peaked and characterized by a rapid rise and a slow fall. Combining our result with the *Ginga* period measurement derived from data acquired on 1989 March 4.9–5.5 UT (Aoki et al. 1992), we obtain a period derivative of $\dot{P} = 1.4 \times 10^{-13}$ s s$^{-1}$.

We searched the GIS data for a signature of an X-ray binary pulsar by looking for long-term period changes due to the expected binary orbital motion. The GIS data were divided into 10 intervals, each of which had a duration of ∼6 ks, and searched for the most significant period over a reasonable range of nearby periods during each time interval. We obtained an upper bound on the period derivative of $\dot{P} \lesssim 2 \times 10^{-11}$ s s$^{-1}$. We conclude that there is no significant variation of the pulse period during this observation.

Finally, we examined the variability of AXS J161730−505505 on a range of timescales longer than several tens of seconds. We rebinned the GIS events in the 3–10 keV band into 64–16384 s time bins and calculated the variance in the light curve. We obtained an upper limit of the rms amplitude of ∼10% of the mean flux at a 90% confidence limit.

As noted by Gotthelf et al. (1997), it is difficult to examine the energy spectrum of AXS J161730−05505 in the soft energy band where diffuse emissions from the SNR shell dominate. We restricted our spectral analysis to the energy range of 3.5–10 keV and extracted photons from the circular region of radius 4′ from AXS J161730−505505. With this selection, spectral contamination from diffuse emission associated with the SNR shell is negligible. We fitted the spectrum with a power-law model modified by interstellar absorption. In our analysis, we fixed the interstellar column density to $N_{\rm H} = 6.8 \times 10^{21}$ cm$^{-2}$, the value obtained for the SNR by Gotthelf et al. (1997), since the low-energy range below 3 keV is severely contaminated by the emission from the SNR. Thus, we obtained a photon index of $\gamma = 1.6^{+0.2}_{-0.3}$, with $\chi^2$/dof = 91/78. The observed flux in the energy range 3.5–10 keV is $3.5 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$, and the intrinsic flux after removing the interstellar absorption is estimated to be $6.4 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$. The pulsed flux reported by Aoki et al. (1992) in the energy range 2.3–13.8 keV is consistent with that derived from the current *ASCA* study, taking into account the statistical and the systematic errors of the results. For the purpose of the following analysis, we estimate the intrinsic flux of the steady part (DC component) of the emission to be $3.3 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ (1–10 keV). Figure 3 shows the unfolded GIS spectrum for the source.

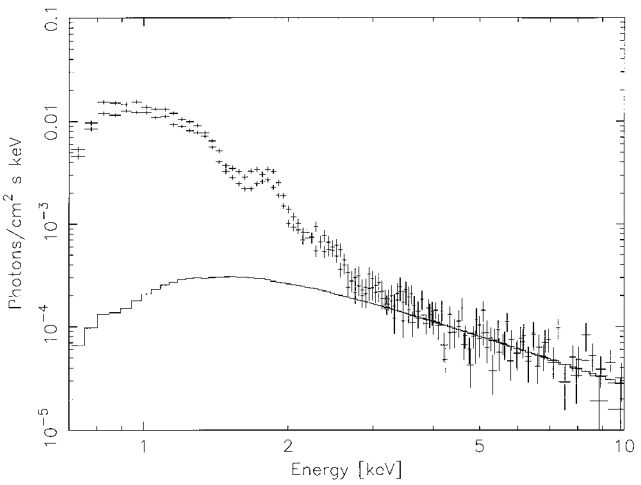


FIG. 3.—Unfolded combined GIS2 and GIS3 energy spectrum of the compact source AXS J161730−505505. Crosses show the data points, and the solid line displays the best-fit power-law model obtained by fitting the spectrum in the 3.5–10 keV energy band. Soft energy photons are dominated by the spatially extended thermal emission from the SNR, while the emission above 3.5 keV predominantly comes from the compact source.

## 3. DISCUSSION

Although the observed pulse-period derivative of the pulsar strongly suggests a rotation-powered origin, we note that the pulsar's period is as short as that of the shortest known accretion-driven pulsar, namely, A0538−668, the 69 ms binary pulsar in the LMC (Skinner et al. 1982). Based on the period alone, it is not clear whether the pulsar is rotation powered or accretion driven (e.g., Nagase 1989; Bildsten et al. 1997).

The pulse profile (Fig. 2) of AXS J161730−505505 is quite different from that of A0538−668, which is doubly peaked (Skinner et al. 1982). It most resembles that of the rotation-powered pulsar PSR B1509−58 (e.g., Saito et al. 1997), which is similarly characterized by a rapid rise and a slow fall. Compared with the accretion-driven pulsars, the pulsar's pulse profile is most similar to that of Cen X-3 (Nagase 1989), whose rotation period of 4.8 s is significantly longer than the pulsar presented herein.

For an assumed circular orbit, we can expect that the pulsar's period will change according to $(r\omega^2/c)\sin\theta\sin i = \dot{P}/P$, where $r$ is the orbital radius, $c$ is the speed of light, $\omega = d\theta/dt$ is the angular velocity of the binary motion, $\theta$ is the phase angle in the orbit, and $i$ is the inclination angle of the orbital plane from our line of sight. We have no information on the factor $\sin\theta\sin i$, while we may make an order of magnitude estimate by using the expectation value, $\langle|\sin\theta|\rangle\langle\sin i\rangle = \frac{1}{2}$. The above equation can be rewritten using the equilibrium condition, $r\omega^2 = GM/r^2$, where $G$ is the gravitational constant and $M$ is the mass of the massive component of the binary. Most companions of the accretion-driven pulsars are massive B stars. Therefore, we may constrain the orbit to $r > 300[(|\sin\theta|\sin i)/(1/2)]^{1/2}[M/(8\ M_\odot)]^{1/2}$ light seconds, which seems incompatible with known binary pulsars.

The probability that the term $\sin\theta\sin i$ is small and that the orbit becomes smaller than that of a typical massive binary Vela X-1, $r = 113.0 \pm 0.4$ lt-s (Nagase 1989) is about 20%. Thus, it is most likely that the source AXS J161730−505505 is a rotation-powered pulsar. As shown below, the lack of long-term variability and the spectral features of the source are consistent with the picture.

We looked for evidence of long-term variability of AXS J161730−505505 that might signal a binary origin since rotation-powered pulsars are not known to show aperiodic time variability. We examined archival *Einstein* and *ROSAT* data and estimated the source count rate in the respective instruments based on the best-fit spectral parameters derived from the GIS data. We used the PIMMS software (Mukai 1993) to convert rates between instruments. In the 1979 *Einstein* HRI and IPC images, we found no significant compact source; this is consistent with a steady source. We found no significant compact source in the *ROSAT* HRI images, which is also consistent with a nonvarying source. In the 38 ks exposure *ROSAT* PSPC image observed in 1991 February–March we also find no evidence of a compact source. If the absorption to the pulsar is the same to the SNR ($N_{\rm H} = 6.8 \times 10^{21}$ cm$^{-2}$), then the pulsar should have been detected in the *ROSAT* PSPC image for the best-fit spectral parameters of the GIS data. This may show that the column density to the pulsar is larger than that to the SNR; however, it is still consistent with the steady emission if the statistical error of the spectral parameters of *ASCA* is taken into account. Further observations of the pulsar are required to determine any definitive long-term variability.

Accretion-driven X-ray pulsars have power-law spectra with typical photon indices of $\gamma \sim 1$ ($0.8 \lesssim \gamma \lesssim 1.5$) and large absorption columns of $N_{\rm H} \gtrsim 10^{22}$ cm$^{-2}$ (Nagase 1989). In contrast, rotation-powered pulsars in the Crab-like SNRs show steeper spectral indices of $\gamma \sim 1.7$ (Lyne & Graham-Smith 1990, p. 86). The spectrum of the present pulsar favors a rotation-powered origin.

The obtained period derivative gives a characteristic age of $\tau = P/(2\dot{P}) = 8.1 \times 10^3$ yr for the pulsar and a spin-down power of $\dot{E} = (2\pi)^2 I\dot{P}/P^3 = 1.6 \times 10^{37} I_{45}$ ergs s$^{-1}$, where $I_{45}$ is the moment of inertia of the neutron star in units of $10^{45}$ g cm$^2$. Assuming that the pulsar is losing its rotational energy via magnetic dipole radiation, $\dot{E} \sim (B_p^2 R^6 \Omega^4)/(6c^3)$, the magnetic field strength at the pole is $B_p = 6 \times 10^{12}$ G. Here, $R \sim 10$ km is the neutron star radius, $\Omega = 2\pi/P$ is the angular velocity of the rotation, and $c$ is the speed of light. The obtained field strength is within the canonical value for a neutron star (e.g., Bailes 1989).

In the standard theory of rotation-powered pulsars, it is expected that the X-ray luminosity of plerionic SNRs should correlate with the spin-down power of their associated pulsars. Seward & Wang (1988) reported an empirical relation based on *Einstein* (0.2–4 keV) data. A similar relation was obtained by Becker & Trümper (1997) using *ROSAT* (0.1–2.4 keV) data. In the following study we employ the relation of Kawai, Tamura, & Shibata (1998), derived using *ASCA* GIS data similar to the data for the pulsar presented herein. Using 10 pulsars of characteristic ages between $1.3 \times 10^3$ yr (Crab pulsar) and $3.1 \times 10^6$ yr (PSR B1929+10) with a median age of $6.4 \times 10^4$ yr, Kawai et al. (1998) found $\log L_{\rm X,nebula} = (33.42 \pm 0.20) + (1.27 \pm 0.17) \times \log(\dot{E}/10^{36})$, where $L_{\rm X,nebula}$ (in ergs s$^{-1}$) is the nebular luminosity in the energy range 1–10 keV exclusive of emission associated with the pulsar. From the measured pulsar spin-down rate, the inferred 1–10 keV nebular luminosity is then $L_{\rm X,nebula} = (9^{+14}_{-6}) \times 10^{34}$ ergs s$^{-1}$. If we assume that the steady emission from the source comes from a synchrotron nebula and that the distance to the pulsar is the same as that of the SNR, the implied luminosity is then

$4.3 \times 10^{33} d_{3.3}^2$ ergs $s^{-1}$, which is significantly smaller than expected.

Although the physical association of the pulsar with RCW 103 is unknown, let us assume here that the pulsar was born in the supernova event that created the remnant and that it received a kick to the north. Then the line-of-sight distance to the pulsar is the same as that to the SNR. Since the pulsar is about $7'$ from the geometrical center of the SNR shell, the expected proper motion of the pulsar is $52 t_{8100}^{-1}$ mas per yr. The kick velocity is then $v_{\rm kick} = 810(\sin\phi)^{-1} d_{3.3} t_{8100}^{-1}$ km $s^{-1}$, where $\phi$ is the angle between the pulsar velocity and our line of sight and $t_{8100}$ is the SNR age normalized to the pulsar characteristic age of 8100 yr. Then its expectation value is $\langle v_{\rm kick} \rangle = 1300 d_{3.3} t_{8100}^{-1}$ km $s^{-1}$ with $\langle |\sin\phi| \rangle = 2/\pi$. This kick velocity belongs to the fastest group measured for young radio pulsars, whose mean projected velocity is $300 \pm 30$ km $s^{-1}$ with some exceeding 1000 km $s^{-1}$ (see Fig. 1 of Lyne & Lorimer 1994).

The characteristic age of the pulsar is twice that estimated for the SNR based on the Sedov self-similar solution, i.e., 4000 yr (Gotthelf et al. 1997). These ages are reconciled by considering two uncertainties. First, the age estimate may be model dependent in the Sedov analysis. Second, the difference between the pulsar characteristic age and the true age depends on the pulsar braking index and on the initial rotation period. If the true age of the pulsar is 4000 yr, the kick velocity becomes as large as $v_{\rm kick} \sim 1600(\sin\phi)^{-1} d_{3.3}$ km $s^{-1}$. If the pulsar is associated with the SNR, the nature of the source, 1E 161348−5055, becomes puzzling, since there are two compact sources associated with a single SNR. However, the small angular distance of the young pulsar to the SNR suggests an association. We speculate that there was a binary system, and that one of the stellar components exploded to create the SNR. If the explosion was symmetric, the more massive component of the stellar remnants, possibly a black hole, may have been left isolated near the center of the explosion. However, if there was a kick velocity, which is expected in supernova explosions to explain many characteristics of the radio pulsars and the low-mass X-ray binaries (Bailes 1989), both compact sources may be neutron stars. In this case, the velocity of the older neutron star is as small as the orbital velocity of the binary, while that of the newer neutron star can be large because of the kick (Bailes 1989). Then, the significantly harder spectrum of AXS J161730−505505 compared with that of 1E 161348−5055 (Gotthelf et al. 1997) supports this picture. No significant coherent pulsation may be expected for the old neutron star. Based on theoretical modelings, Popov (1998) claims that the compact source near the center of RCW 103 is an accreting neutron star rather than an accreting black hole. Future studies are needed to resolve these possibilities.

We have reported the discovery of 69 ms coherent pulsations from the X-ray source AXS J161730−505505. The timing and spectral analysis of the source suggests that it is a rotation-powered pulsar. From this point of view, high spatial resolution observations may reveal an extended synchrotron nebula around the source. Searches for counterparts at other wavelengths may prove quite fruitful.

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## REFERENCES

Aoki, T., Dotani, T., & Mitsuda, K. 1992, IAU Circ. 5588
Bailes, M. 1989, ApJ, 342, 917
Becker, W., & Trümper, J. 1997, A&A, 326, 682
Bildsten, L., et al. 1997, ApJS, 113, 367
Brazier, K. T. S., & Becker, W. 1997, MNRAS, 284, 335
Caswell, J. L., Murray, J. D., Roger, R. S., Cole, D. J., & Cooke, D. J. 1975, A&A, 45, 239
Gotthelf, E. V., Petre, R., & Hwang, U. 1997, ApJ, 487, L175
Gotthelf, E. V., & Vasisht, G. 1997, ApJ, 486, L133
Helfand, D. J., Becker, R. H., & White, R. L. 1995, ApJ, 453, 741
Kawai, N., Tamura, K., & Shibata, S. 1998, ApJL, submitted
Lyne, A. G., & Graham-Smith, F. 1990, Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Lyne, A. G., & Lorimer, D. R. 1994, Nature, 369, 127
Makishima, K., et al. 1996, PASJ, 48, 171
Mukai, K. 1993, Legacy, 3, 21
Nagase, F. 1989, PASJ, 41, 1
Ohashi, T., et al. 1996, PASJ, 48, 157
Popov, S. B. 1998, Astron. Astrophys. Trans., in press (astro-ph/9708044)
Saito, Y., Kawai, N., Kamae, T., & Shibata, S. 1997, in Proce. Fourth Compton Symp., ed. C. D. Dermer, J. D. Kurfess, & M. S. Strickman (New York: AIP), in press
Seufert, E. 1995, *ASCA* Newsl., 3, 42
Seward, F. D., & Harnden, F. R., Jr. 1982, ApJ, 256, L45
Seward, F. D., Harnden, F. R., Jr., & Helfand,D. J. 1984, ApJ, 287, L19
Seward, F. D., & Wang, Z.-R. 1988, ApJ, 332, 199
Skinner, G. K., Bedford, D. K., Elsner, R. F., Leahy, D., Weisskopf, M. C., & Grindlay, J. 1982, Nature, 297, 568
Tamura, K., Kawai, N., Yoshida, A., & Brinkmann, W. 1996, PASJ, 48, L33
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
Torii, K., Kinugasa, K., Hashimotodani, K., Tsunemi, H., & Slane, P. 1998, PASJ, submitted
Torii, K., Tsunemi, H., Dotani, T., & Mitsuda, K. 1997, ApJ, 489, L145
Tuohy, I., & Garmire, G. 1980, ApJ, 239, L107
Vasisht, G., & Gotthelf, E. V. 1997, ApJ, 486, L129
Weiler, K. W., & Panagia, N. 1978, A&A, 70, 419